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ORIGINAL INVESTIGATION

Narrowed Posterior Nasal Airway Limits Efficacy of Anterior Septoplasty

David A. Campbell, MD,[1] Masoud Gh. Moghaddam, PhD,[2]
John S. Rhee, MD, MPH,[1] and Guilherme J.M. Garcia, PhD[1,2,*]

Abstract

Background: Predicting symptomatic relief after septoplasty has been difficult. Minimal cross-sectional area (mCSA) measured by acoustic rhinometry and airflow resistance (*R*) measured by rhinomanometry have been used to select surgical candidates with mixed success. An important assumption is that mCSA and resistance are tightly coupled, but studies have reported weak or no correlation. Recently, we proposed the Bernoulli Obstruction Theory as an explanation, where tight coupling between mCSA and *R* is only predicted below a critical mCSA (A_{crit}).

Methods: The nasal airway and septum of 10 healthy subjects were reconstructed from computed tomography scans. Simulated anterior septal deviations of increasing severity were created. Computational fluid dynamics simulations were performed to quantify mCSA, resistance, and flow in the healthy septum model and four simulated septal deviation models for each subject (total of 50 models).

Results: A tighter coupling between mCSA and resistance was found below A_{crit}, estimated to be 0.20 cm^2 (a very severe deviation). Above A_{crit}, enlarging the mCSA had a smaller effect in patients with narrower cross-sectional area in the postvalve region (CSA_{PV}).

Conclusions: Two patterns of flow increase are expected with septoplasty. Below A_{crit}, enlarging mCSA predictably increases flow. Above A_{crit}, the effect size of increasing mCSA depends on CSA_{PV}. Unrecognized small CSA_{PV} may explain persistent sensation of nasal obstruction after septoplasty. Our data suggest that inferior turbinate reduction ipsilateral to a septal deviation may amplify airflow benefits after septoplasty in patients with a narrow CSA_{PV}.

Introduction

Surgeons treating nasal airway obstruction (NAO) are frequently frustrated by failure of subjective symptoms to improve after a technically successful surgery. Since the technical goal of NAO surgery is to increase cross-sectional area (CSA) of the constricted nasal cavity, two key assumptions are made: (1) the increased CSA will reduce resistance and improve airflow and (2) the increased airflow will improve subjective sensation of nasal patency. Although studies have shown consistent ability of surgery to increase the airspace CSA,[1–4] 11–53% of patients have persistent subjective symptoms postoperatively.[5–10] These results indicate the mentioned assumptions do not apply in every case.

Objective measures of nasal form and function have been developed in an effort to predict surgical responders. The most widespread tools are acoustic rhinometry (AR) to measure form, and rhinomanometry to measure function. AR uses reflected sound waves to measure CSA along the nasal passage, estimating the minimal CSA (mCSA). Rhinomanometry directly measures pressure differences and airflow to determine nasal resistance. Several studies have applied these tools to examine the second assumption mentioned: increased airflow will improve subjective sensation of nasal patency. Unfortunately, many studies found a lack of correlation between objective and subjective measures of nasal airflow.[11–17] A 2015 clinical consensus statement on septoplasty was unable

[1]Department of Otolaryngology and Communication Sciences, Medical College of Wisconsin, Milwaukee, Wisconsin, USA.
[2]Department of Biomedical Engineering, Marquette University & The Medical College of Wisconsin, Milwaukee, Wisconsin, USA.
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*Address correspondence to: *Guilherme J.M. Garcia, PhD, Department of Biomedical Engineering, Medical College of Wisconsin, 8701 Watertown Plank Road, Milwaukee, WI 53226, USA,* Email: ggarcia@mcw.edu

KEY POINTS

Question: Can surgeons better predict patients more likely to report relief from nasal airway obstruction symptoms after septoplasty?

Findings: Computational fluid dynamics studies were performed on nasal cavities with virtually created anterior septal deviations of varying severity. Correcting anterior deviations of similar severity yielded greater airflow improvement if the posterior nasal airway ipsilateral to the deviation was wider.

Meaning: Septoplasty addressing an anterior septal deviation is less efficient at increasing airflow if the posterior nasal airway is narrow. Adjunct procedures aimed at enlarging the posterior nasal airway can increase the impact that anterior septoplasty has on nasal airflow.

to reach consensus on the utility of AR and rhinomanometry to predict surgical responders.[18]

Fewer studies have examined the first assumption: increased CSA will reduce resistance and improve airflow. A recent literature review of studies comparing AR and rhinomanometry found that 10 out of 11 studies reported moderate or no correlation between mCSA and resistance, with only one study reporting a strong correlation.[19] Our group has been using computational fluid dynamics (CFD) to examine this apparent disconnect between nasal form and function. CFD is an emerging technology that quantifies nasal airflow based on three-dimensional (3D) nasal airway models built from computed tomography (CT) scans. We proposed the Bernoulli Obstruction Theory as an explanation for the disconnect.[19,20] The theory predicts a tight coupling between mCSA and resistance only when a single constriction is disproportionately responsible for nasal resistance. We defined a critical mCSA (A_{crit}) as the mCSA corresponding to a threshold for abnormal resistance.[19] The CFD simulations confirmed a strong correlation between mCSA and nasal resistance below A_{crit} and only a moderate correlation above A_{crit}.[19] The goal of this study is to use CFD to systematically examine how the Bernoulli Obstruction Theory dictates nasal airflow in patients with septal deviations.

Materials and Methods

Study design

Geometry-deforming software was used to create leftward septal deviations of increasing severity in 3D reconstructions of the nasal cavity of 10 healthy subjects. CFD simulations were performed to quantify nasal airflow, resistance, and mCSA.

Patient selection

This study was approved by the Institutional Review Board of the Medical College of Wisconsin. In a previous publication, we developed a database of nasal CFD models of 47 healthy subjects without NAO symptoms.[21] The mean (±standard deviation, SD) unilateral mCSA in these healthy subjects was $0.66 \pm 0.21\ cm^2$. As a wide range of mCSA was required for experimentation in this study, patients were excluded if either nasal cavity had mCSA $<0.60\ cm^2$. The first 10 subjects with straight septa and mCSA $>0.60\ cm^2$ were selected for analysis.

Construction of original models

Cone beam CT scans were imported into Mimics™ (Materialise, Ann Arbor, MI), where the 3D nasal airspace was reconstructed using a threshold range from −1024 to −300 HU. The 3D anatomy of the septum was reconstructed using a threshold range from −300 to 3071 HU.

Construction of simulated septal deviation models

All simulated deviations were leftward and in the nasal valve region as anterior deviations have the greatest impact on nasal airflow.[22] The healthy septum geometries were transferred to the geometry-deforming software Sculptor Morph™ 1.8.4 (Optimal Solutions Software, LLC, Idaho Falls, ID), where simulated septal deviations were created. Deviations were centered at the first coronal slice posterior to the left nostril and their anterior–posterior length was limited to 30% of the distance from nasal tip to choana. First, a model with very severe septal deviation was created and transferred back to Mimics™ to ensure it did not obstruct the nasal airspace entirely. Second, three additional models were created in which the horizontal leftward displacement of the septum was 75%, 50%, and 25% of the displacement in the first model. This process was repeated for all 10 subjects. The deviated septa were exported back to Mimics, where nasal airspace models were created. We compared simulated septal deviations to real septal deviations in NAO patients to ensure the simulated deviations mimicked naturally occurring deviations (Fig. 1).

CFD simulations

To quantify nasal airflow, the geometry must be divided in a large number of grid points, where air velocity and pressure can be defined. This grid was created in ICEM-CFD™ (ANSYS, Canonsburg, PA) with ~6 million tetrahedral elements. This mesh size was determined based on a mesh density test and has been shown to provide a pressure–flow curve in good agreement with in vitro experiments.[23,24] Quality of the tetrahedra was checked to ensure an aspect ratio >0.3 to avoid distorted elements and optimize accuracy.

Steady-state inspiratory airflow simulations were conducted in Fluent 14.0 (ANSYS, Inc.) assuming laminar

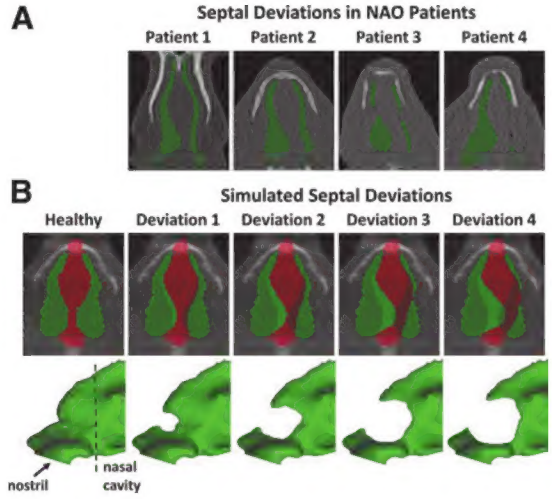

Fig. 1. Creation of models with simulated septal deviations. **(A)** Coronal CT images of four different NAO patients with septal deviations of varying severity. **(B)** (Top) Coronal CT images showing simulated septal deviations with increasing severity within the same subject (red, nasal septum; green, nasal airspace). (Bottom) Lateral view of anterior portion of the three-dimensional reconstruction of the left nasal cavity. Dashed line represents the location of the coronal section depicted. CT, computed tomography; NAO, nasal airway obstruction.

airflow and using the following boundary conditions: (1) inlet pressure at the nostrils = 0 Pa gauge, (2) no slip at the walls, and (3) outlet pressure set to a constant value so that the pressure drop from nostrils to choana was 15 Pa. The outlet pressure required to obtain a transnasal pressure drop of 15 Pa was determined by running preliminary simulations to fit the power law $P_{choana} = a(P_{outlet})^b$, where P_{choana} is the choana pressure, P_{outlet} is the outlet pressure, and a and b are fitted constants. The selection of a laminar CFD model is supported by experiments[23,25] and by the fact that the Reynolds number (based on the mCSA) ranged from 397 to 2358 in our 50 models. Models with more severe septal deviations had lower Reynolds numbers due to the reduction in flow rate. Unilateral nasal resistance (R) was defined as $R = \Delta P/Q$, where $\Delta P = 15$ Pa and Q is the unilateral flow rate. Airflow partitioning was defined as unilateral airflow in the left cavity divided by bilateral airflow.

Computational streamline rhinometry

Computational streamline rhinometry is a method for computing CSA of the nasal cavity perpendicular to flow streamlines representative of the main flow direction.[19] The airspace CSA is measured in planes perpendicular to 10 streamlines, and the average CSA is plotted against a normalized distance from nostrils to choana. mCSA is the smallest CSA among the 10 streamlines, and the average CSA in the postvalve (CSA_{PV}) is the average CSA from normalized distance 0.4 to 1.0 (Supplementary Fig. S1).

Bernoulli obstruction theory

A complete description of the Bernoulli Obstruction Theory (also known as orifice flow) can be found in Garcia et al.[19] and other publications.[20,26–28] The Bernoulli and continuity equations are combined to derive the orifice flow equation that describes flow through a tube with a single constriction

$$Q = C_d\ \mathrm{mCSA}\sqrt{\frac{2\Delta P}{\rho|1-\beta^2|}}, \quad (1)$$

where C_d is a constant, $\rho = 1.204\ \mathrm{kg/m^3}$ is air density, and the parameter $\beta = \mathrm{mCSA}/A_0$ is the ratio of the CSA at the constriction (mCSA) to the tube CSA upstream and downstream of the constriction (A_0).[20] As the constriction narrows, mCSA $\rightarrow 0$, $\beta \rightarrow 0$, and flow becomes directly proportional to mCSA ($Q \propto$ mCSA). In this limit of a severe constriction (orifice flow), nasal resistance is predicted to be inversely proportional to mCSA ($R \propto \mathrm{mCSA}^{-1}$) for a constant ΔP.

We arbitrarily define a critical mCSA (A_{crit}) as the mCSA threshold to achieve a healthy unilateral nasal resistance.[19] In healthy individuals, Borojeni and coauthors (2020) found unilateral nasal resistance to be 0.10 ± 0.07 Pa·s/mL.[21] Defining the critical resistance (R_{crit}) as 2 SDs above the mean ($R_{crit} = 0.10 + 2 \times 0.07 = 0.24$ Pa·s/mL), A_{crit} is calculated by substituting R_{crit} into the power law equation

$$R = a\ (\mathrm{mCSA})^b, \quad (2)$$

where a and b are constants fitted to the CFD results.

Statistical analyses

Two-tailed paired Student's t-tests were used to test the hypothesis that variables in models with simulated septal deviations were statistically different from the healthy (straight septum) model. Differences were considered statistically significant for p-values <0.05. The Pearson correlation coefficient (r) was computed to quantify the correlation between two variables.

Results

Effect of simulated septal deviations on mCSA

Airspace CSAs were computed perpendicular to flow streamlines in the 10 healthy models and 40 models with simulated septal deviations (Supplementary Fig. S2).

The mean (±SD) mCSA in the left cavity was 0.80 ± 0.18 cm^2 in the healthy models. As severity of septal deviation increased, left-side mCSA decreased to 0.64 ± 0.14, 0.38 ± 0.10, 0.19 ± 0.07, and 0.09 ± 0.06 cm^2 in the four models with simulated septal deviations of each subject (Supplementary Table S1).

Effect of simulated septal deviations on nasal airflow

Bilateral and unilateral airflows were averaged for the 10 models for each degree of septal deviation (Fig. 2A). Left cavity airflow and bilateral airflow decreased in proportion to the severity of septal deviation, whereas airflow in the right cavity was mostly insensitive to the deviation (Fig. 2A). Airflow partitioning was 46% ± 13% in the 10 healthy models demonstrating a nearly symmetrical flow distribution between the left and right nostrils. Airflow partitioning decreased to 42% ± 13%, 33% ± 10%, 23% ± 7%, and 12% ± 6% in models with deviations 1, 2, 3, and 4, respectively, demonstrating increasing asymmetry in flow distribution between nostrils with increasing severity of septal deviation (Fig. 2B).

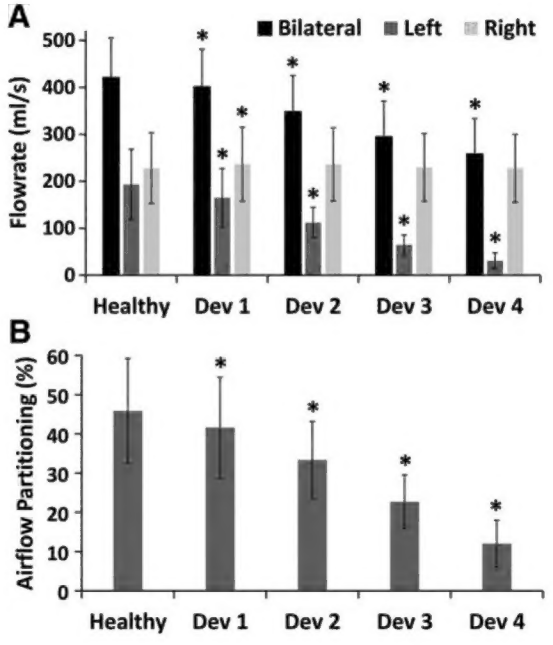

Fig. 2. **(A)** Bilateral and unilateral airflows (mean ± SD) in the healthy model and models with simulated septal deviations of increasing severity at a 15 Pa pressure drop from nostrils to choana. **(B)** Percentage of airflow passing through the left nostril. Asterisk (*) denotes statistically significant difference compared with healthy model ($p < 0.05$).

Relationship between nasal resistance and mCSA

Resistance and flow are interchangeable since resistance was calculated from flow measurements at a constant ΔP of 15 Pa. Left nasal resistance and flow were plotted separately against mCSA and power law curves were fit (Fig. 3A, C). A_{crit} was calculated to be 0.20 cm^2 and both plots were split at A_{crit} (Fig. 3B, D). Consistent with our prior study,[19] we found a near inverse relationship between resistance and mCSA ($R \propto \text{mCSA}^{-1}$) and weaker correlation as mCSA increases. Large resistance changes were seen below A_{crit} with a relative plateau above A_{crit}.

Predicting the effect size of septoplasty

To interpret our results in the context of septoplasty, each septal deviation model represents a possible preoperative state, whereas the corresponding healthy model with its straight septum represents the postoperative outcome. Two hypothetical patients were considered starting with the same mCSA (Supplementary Fig. S3A). Both undergo technically successful septoplasty with identical increases in mCSA, but Patient A achieves a far better flow rate increase (''robust'' response) than Patient B (''weak'' response). When individual curves were fit to

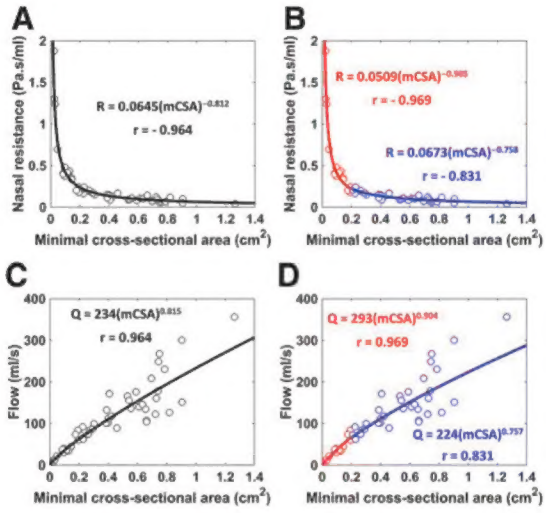

Fig. 3. Correlation between nasal form and function. **(A)** Unilateral nasal resistance versus mCSA of all left nasal cavities ($n = 50$ models). A power law curve fit was used to estimate $A_{crit} = 0.20\ cm^2$ as the threshold for abnormal nasal resistance. **(B)** Separate curve fits to nasal cavities with mCSA below and above A_{crit} revealed a stronger correlation below A_{crit} ($|r| = 0.969$) than above A_{crit} ($|r| = 0.831$). **(C, D)** The same analysis for left-side airflow versus mCSA. mCSA, minimal cross-sectional area.

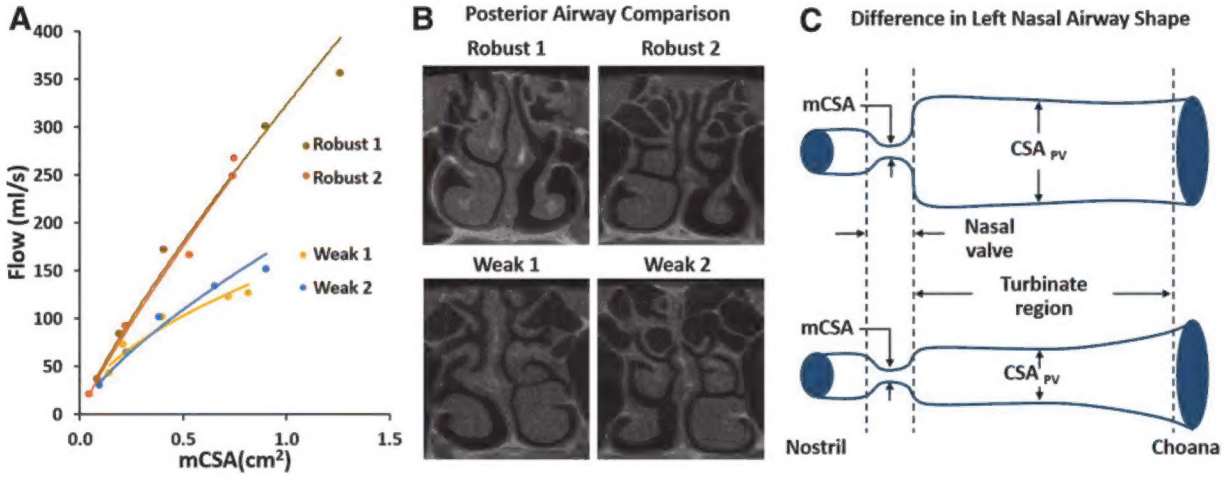

Fig. 4. Differentiating predicted septoplasty responders and nonresponders. **(A)** Left-side flow versus mCSA in two patients with a robust response to septoplasty and two patients with a weak response to septoplasty. **(B)** Coronal CT images of postvalve region (posterior to deviation). Note the wide posterior left airway in robust responders and narrow posterior left airway in weak responders. **(C)** Proposed schematic of unilateral nasal airway in robust responders (top) and weak responders (bottom). CSA_{PV}, average cross-sectional area of postvalve airway.

the five data points available for each patient, a separation of the curves was observed above A_{crit} with a range of very robust to very weak septoplasty responders (Supplementary Fig. S3B).

Examination of the CT scans from patients in each extreme of septoplasty response revealed that patients with a robust response to septoplasty had decongested left inferior turbinates resulting in a wide left postvalve airway, whereas patients with weak response had congested left inferior turbinates resulting in a narrow left postvalve airway (Fig. 4). This observation led to the hypothesis that the response to septoplasty depends not only on the mCSA, but also on the average CSA of the postvalve airway (CSA_{PV}).

The response to septoplasty was quantified as the flow increase (ΔQ) associated with an increase in mCSA from 0.20 to 0.60 cm^2, namely (Fig. 5A),

$$\Delta Q = Q_{0.6} - Q_{0.2},$$

where $Q_{0.6}$ and $Q_{0.2}$ are the unilateral flows corresponding to mCSA = 0.60 cm^2 (a healthy nose) and mCSA = A_{crit} = 0.20 cm^2 (a constricted nose) estimated from the best fit to the five data points available for each patient. As hypothesized based on visual inspection of the CT scans, there was a strong correlation between the response to septoplasty and the average CSA of the postvalve airway ($r = 0.937$) (Fig. 5B) with wider CSA_{PV} leading to better flow increases after septoplasty.

Air pressure colormaps were created to visualize the pressure reduction along the left nasal cavity (Fig. 6). As defined by the CFD boundary conditions, each model had a pressure drop from 0.0 Pa at the nostril to −15 Pa at the choana. With progressive septal deviation, the pressure drop becomes more concentrated at the nasal valve, visualized as a more abrupt change from red (0 Pa) to blue (−15 Pa). A robust septoplasty responder (Fig. 6A: $CSA_{PV} = 2.36$ cm^2) was compared with a weak septoplasty

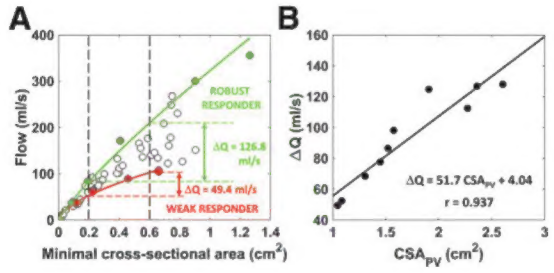

Fig. 5. Predicting septoplasty efficacy. **(A)** Unilateral flow (left cavity) of 10 healthy models and 40 models with simulated septal deviations of varying severity. The response to septoplasty was defined as the flow increase (ΔQ) associated with an increase in mCSA from 0.20 to 0.60 cm^2. **(B)** The response to septoplasty is directly proportional to the mean CSA in the postvalve airway (CSA_{PV}).

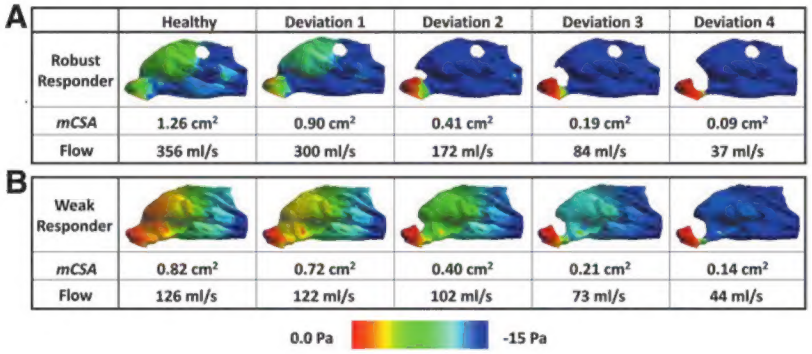

Fig. 6. Left nasal cavity air pressure fields in two representative subjects. In both, as the severity of the septal deviation increases and unilateral mCSA becomes smaller, unilateral flow is reduced and the pressure drops become concentrated at the nasal valve. **(A)** The robust septoplasty responder has a wide postvalve airway ($CSA_{PV} = 2.36\,cm^2$). **(B)** The weak septoplasty responder has a narrow postvalve airway ($CSA_{PV} = 1.09\,cm^2$).

responder (Fig. 6B: $CSA_{PV} = 1.09\,cm^2$). Although the Deviation 2 models had similar mCSA in these two patients ($0.41\,cm^2$ vs. $0.40\,cm^2$), left-side airflow was much higher in the robust responder (172 mL/s) than in the weak responder (102 mL/s). This is explained by the fact that the postvalve airway has negligible resistance in the robust responder, but a significant pressure drop in the postvalve airway is observed in the weak responder (Fig. 6).

Discussion

A long-standing frustration in the surgical management of NAO has been that technically successful surgery does not always result in symptomatic relief. As stated in the introduction, a surgeon makes two assumptions with NAO surgery: (1) increasing the mCSA of the nasal airway will reduce resistance and improve airflow, which (2) will lead to improvement in the subjective sensation of airflow. The first statement assumes a strong correlation between nasal form and function that has not been consistently shown in the literature.[19] Based on a CFD study of NAO patients, we recently proposed the Bernoulli Obstruction Theory as an explanation for this lack of strong correlation.[19] Interestingly, the same theory was applied in the 1980s by Warren[26] to develop a technique to estimate an effective CSA of the nasal cavity based on flow measurements. After validating their technique with experiments in cylindrical tubes, Warren and coauthors applied it to normal subjects and patients with impaired nasal breathing.[26,29,30] They reported an inverse relationship between resistance and area such that airway area has a much greater effect on nasal resistance when the area is $<0.4\,cm^2$. They also estimated that the nose becomes flow limited when the area $<0.18\,cm^2$.[30] This study confirms and expands on these findings by demonstrating that the relationship between R and mCSA is influenced by the area in the postvalve region.

Applying the Bernoulli Obstruction Theory to NAO may explain septoplasty failure rates as well as predict septoplasty responders. Although commonly assumed for any mCSA, a strong correlation between form and function should only be expected below mCSA of $0.20\,cm^2$, when it would be disproportionately responsible for the resistance. An mCSA of $0.20\,cm^2$ represents a very severe septal deviation on anterior rhinoscopy.[11–17] Most NAO patients have mCSA $>0.20\,cm^2$,[19] thus reliable and robust increases in airflow should not always be assumed after septoplasty. This does not imply that patients with mCSA $>0.20\,cm^2$ should not be offered septoplasty, but that predicting surgical responders in this group becomes important.

Clinically speaking, our findings encourage the NAO surgeon to confidently offer septoplasty for patients with anterior septal deviations that cause a severe narrowing. In a patient with a moderate narrowing from a septal deviation, the surgeon can be more confident when the posterior airway is open. When the posterior airway is not wide, septoplasty alone should be offered with caution. The surgeon should have a low threshold to assess for ways to widen the ipsilateral posterior airway (turbinate reduction, concha bullosa resection, etc.) at the time of septoplasty to increase CSA_{PV}. Studies have shown benefit of turbinate reduction at the time of septoplasty, but cite contralateral compensatory hypertrophy as the source of benefit.[18,31,32] Although turbinate reduction is commonly performed to address turbinate hypertrophy contralateral to the deviation, our study suggests that ipsilateral turbinate reduction may amplify the impact of septoplasty.

A multitude of factors influence a subjective symptom, and there have been arguments that a weak or lack of correlation between objective and subjective measures of NAO should not be surprising.[33,34] Clear counseling and shared decision making are paramount in NAO treatment since only the patient knows whether expectations have been met. If two patients are promised "good increase in airflow" after surgery, one may be satisfied with a 50% improvement and the other may be dissatisfied with the same result because they were expecting a 100% improvement. If the second patient was told preoperatively to anticipate a 50% increase in airflow, they may decline surgery or may be satisfied because their preoperative expectation was met. In the future, estimates of the mCSA and CSA_{PV} from CT scans or other techniques may provide a method to estimate the expected percentage change in flow in each cavity. Ability to clearly communicate expected objective benefit after surgery would be a powerful tool in the preoperative discussion. It may change a patient's expectations, leading to increased satisfaction. Alternatively, if patient expectations would not be met by septoplasty, it may avoid unnecessary surgery or encourage adjunct procedures.

One limitation of this research is that the radiodensity threshold used to segment the nasal airspace from CT scans has a substantial impact on the CSAs and airflow resistance of CFD models.[35–37] To our knowledge, the optimal segmentation threshold to reproduce in vivo measurements of nasal resistance is unknown. A segmentation threshold of −300 HU was used in this study to be consistent with previous publications from our group.[19,21] While using a different segmentation threshold could affect some numbers in this article (such as the critical mCSA of 0.20 cm^2), the key concepts presented here are expected to remain true.

Conclusions

The Bernoulli Obstruction Theory predicts a strong correlation between changes in mCSA and nasal airflow only when the constriction being addressed is disproportionately responsible for the resistance.[19] We predict this strong correlation only below an mCSA of 0.20 cm^2, which is a very severe septal deviation. Above mCSA of 0.20 cm^2, a wider postvalve airway ipsilateral to the deviation predicts better airflow response to septoplasty. When the ipsilateral posterior nasal cavity is wide, anterior deviations are disproportionately responsible for nasal resistance, thus increases in mCSA >0.20 cm^2 will continue to cause significant and predictable increases in flow. In contrast, when the postvalve airway is narrow, resistance is more distributed along the nasal airway, thus correction of an anterior septal deviation may not be sufficient to normalize flow. In conclusion, surgeons should examine the ipsilateral nasal airway posterior to septal deviations and have a low threshold to address the postvalve region as this may increase the efficacy of the septoplasty.

Author Disclosure Statement

No competing financial interests exist.

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Supplementary Material

Supplementary Figure S1
Supplementary Figure S2
Supplementary Figure S3
Supplementary Table S1

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